ENSURING NMD AFFORDABILITY THROUGH THE PSA_oR_m PROCESS

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Abstract

In 1996, the National Missile Defense (NMD) Program was redirected from a Technology Readiness Program focusing on demonstrating technologies to a Deployment Readiness Program (DRP). The DRP's objective is developing and maintaining a capability to field the system three years following a deployment decision. With this redirection came the need to balance cost and performance in the new Acquisition Reform environment. This led to system characteristics that prompted a change in the way that Reliability, Availability and Maintainability parameters are treated in the system engineering process. In the Technology program, hardware developers were most concerned with single shot reliability to ensure a successful test. Deployment Readiness, however, requires that hardware and software be developed to support overall life cycle System Effectiveness. System designs must be maintainable and must incorporate redundancy and backup modes and circuits to efficiently provide the very high probability of threat negation required by the US Space Command, the NMD User. In order to meet System Effectiveness requirements of the large, complex NMD system, the User and the Ballistic Missile Defense Organization's NMD Joint Program Office (developer) agreed to replace the requirement for specified system level Operational Availability with a balanced approach focusing on mission effectiveness. This approach also provides the greatest possible trade space where contractors are permitted the freedom to balance Performance, Survivability, Operational Availability, and Mission Reliability, commonly referred to as the PSA_oR_m. This paper describes the NMD approach and rationale, and recommends it as the optimal approach for meeting user system effectiveness requirements for very large, complex systems.

Introduction

In 1996 the Secretary of Defense redirected a National Missile Defense development from a Technology Readiness Program focusing on demonstrations, to a Deployment Readiness Program. The DRP's objective is to develop and maintain a capability to field the system three years following a deployment decision. The redirection, the need to effectively balance cost and performance trade-offs in the new Acquisition Reform environment, and the larger, complex NMD system characteristics prompted a change in the way that Reliability, Availability and Maintainability PSA_oR_m* parameters are treated in the system engineering process.

National Missile Defense is often characterized as a "system of systems." The NMD System is comprised of subsystems (called Elements) that are large and complex enough to be "systems" in their own right. See Figure 1.

The objective of the National Missile Defense program is to develop and demonstrate the capability to protect the fifty United States against small scale ballistic missile attacks. NMD is structured on a 3+3 timeline. Three years are allocated to develop and demonstrate a ballistic missile defense capability. Fielding an initial capability would then be required three years following a deployment decision. An integrated system test is planned at the end of fiscal year 1999. Deployment of the NMD system could be required with an Initial Operational Capability in place as early as 2003.

The NMD 3+3 program is being managed in the Acquisition Reform Environment, which places great emphasis on innovative approaches and streamlined acquisition management and documentation. The goal of acquisition reform is to acquire new weapons that meet requirements at affordable cost and on a schedule that allows the DoD to counter a specific threat. This concept requires the Program manager to set cost goals early, and then manage engineering trades aggressively to meet the cost goals. This requires identifying performance and cost parameters

* Shown elsewhere as PSAR.

early in the acquisition process. Once the cost is established, it becomes a constraint that must be managed and controlled. This concept is called "CAIV"—Cost As An Independent Variable. The paper describes the process being used by NMD as a key tool to manage to the CAIV requirement.

NMD capability is being designed to meet requirements set by the Commander-in Chief, North American Air Defense (NORAD) against threat scenarios developed and certified by the Defense Intelligence Agency (DIA). Since the requirements and threats are broad based rather than specific, the NMD System Engineer has developed a "plug and defend" approach in which Elements and basing options remain flexible through the development period in order to meet evolving threats. However, an exception to this approach is required for the site activation planning necessary to meet the 3 year deployment objective. Consequently, a "prototype site" has been identified for planning.

NMD system architecture and site location have been identified for deployment planning and site activation. A prototype NMD site has been specified in the North Dakota Anti-Ballistic Missile (ABM) Defense area specified by the 1972 ABM Treaty between the United States and the Union of Soviet Socialist Republics. NMD planning architecture (see Figure 1) is described below.

- Twenty Ground Based Interceptors (GBI) consisting of a Booster and Exoatmospheric Kill Vehicle (EKV)
- Four Upgraded Early Warning Radars (UEWRs)
- Five Deployed X-Band Radars
- Five Battle Management, Command and Control (BMC3) Nodes
- Geographically Separated In-Flight Interceptor Control Systems (IFICS) (Sites TBD)
- Defense Support Program (DSP) or Space-Based Infrared System (SBIRS) Support (based on availability)

US Space Command system performance requirements and the DIA threat scenarios are the design-to parameters used by the NMD system engineer to design the missile defense system architecture. In addition to performance requirements, Space Command documents specify design-to system operational suitability (system supportability) parameters.

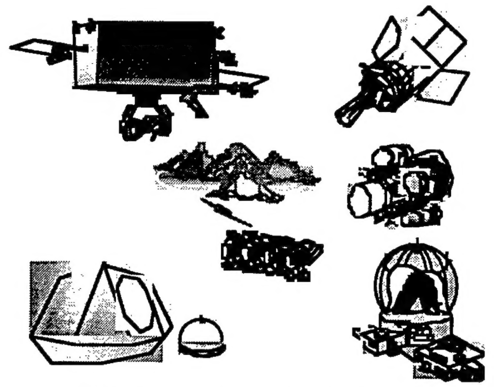

Figure 1. NMD Architecture Elements

In order to meet the separate but complementary objectives of operational effectiveness and life cycle cost control, the NMD Program Manager will incorporate a structured Reliability, Availability, and Maintainability (RAM) program in development contracts. RAM will be built around the new BMDO/US Space Command approach to system effectiveness that eliminates specifying Operational Availability at system level, relying rather on specifying system effectiveness (probability of reentry vehicle (RV) negation) which includes availability.

"Design-to" NMD Operational Suitability requirements will be met by specifying that each NMD contract provide incentives to ensure that RAM performance will be met at the lowest possible life cycle cost. For most systems, an increase in the design reliability results in higher initial acquisition cost either due to costs of higher rated components or redundancy, or both. Therefore, potential operations and support (O&S) savings (that would result from this reliability) must be carefully validated.

The trade between initial acquisition cost and O&S cost for each element is shown generically in Figure 2. In this simplified figure the curve labeled LCC is simply the sum of acquisition costs and O&S costs. Increasing design reliability requires a higher initial acquisition cost but will result in lower O&S costs over the life cycle. The LCC curve therefore has a "bucket" shape where LCC will be minimized for a particular design reliability. The choice of design reliability will differ depending on the anticipated life cycle. For example a 20 year life cycle would justify paying more up front for acquisition (e.g. for redundancy) than would a 10 year life cycle.

PSAR vs. System Level Operational Availability

In 1996, the system engineer was faced with taking user requirements and translating them into allocations for the component so that the entire system worked synergistically to meet the assigned missions. On the surface, this sounded like the typical challenge for any system. However, there were several factors that compounded the task. First, each component is large and complex enough to be considered as a system itself. Second, depending on the threat posited for the system, there may be some redundancy between the components. That is, a component might accomplish some of the functions of another component. Also, some components may accomplish multiple functions for the system. And finally, different threats, and different threat trajectories, resulted in different reliability, availability, and maintainability requirements for each of the components.

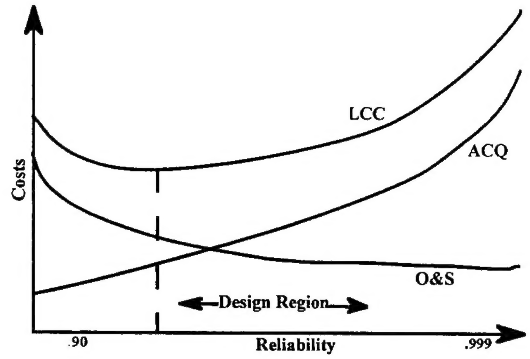

Figure 2. Balancing Acquisition and O&S Costs

The first step in adopting the new approach was achieving community agreement that system performance (a measure of overall operational effectiveness expressed as a target negation requirement) and system availability (expressed as operational availability) were not the same thing. For the NMD System, the negation key performance parameter stated by the user was believed to be high enough to drive the system operational availability value above the user requirement. The system engineering contractor contended that specifying both parameters added nothing to the "goodness" of the system while needlessly constraining the design space, not limiting system downtime, and potentially forcing additional assets to be added to the architecture.

Next, the system architecture was modeled against an array of threats to determine the component platform performance levels necessary to achieve the system-level negation requirements. The performance levels were considered a function of performance, survivability, operational availability, and mission reliability (PSAR). For example, each interceptor or radar was considered a platform and was assigned PSAR values.

With the platform values assigned, it was then possible to roll these up to arrive at component (element) values based on the architecture and the threat being considered. With these derived values, system operational availability was calculated and it exceeded the original user requirement. This rationale was used to support dropping the system operational availability requirement in favor of the system effectiveness parameter. This action provided the system engineers with the full trade space of PSAR.

It may not be possible to design the system to operate at the absolute minimum of the LCC curve shown in Figure 2 because System Effectiveness requirements stated by the user may require a design reliability to the right of the absolute minimum on the LCC curve. The System Engineer's approach to this is to flow down a PSAR requirement to each element. The design contractor is then allowed to trade between performance, survivability, availability, and reliability.

To illustrate the PSAR process, consider the following example. Suppose the requirement is levied on the GBI designer that he must demonstrate how he would increase the single shot kill probability from his initial design of .80 to a higher value of .90. Using the PSAR process, RAM parameters are in the same trade space as the technical design parameters of the booster and EKV. One approach to increasing Pk might be to increase divert capability to correct for targeting and handover errors. Another approach might be to increase the booster reliability or to add redundancy to the IFICS transceiver on the EKV to ensure receipt of the in-flight target update (IFTU) and target-object map (TOM). Each approach will have a different impact on costs, and the contractor will recommend the design that meets system objectives with the lowest risk to cost and schedule.

The following example is provided to illustrate the PSAR approach to meet User performance

requirements without specifying Operational Availability at the NMD system level. The example is composed of purely notional numerical values. Any reference to companies, materials, processes, or phenomenology is strictly fictitious. The term booster is used to refer to the GBI booster and not the threat booster.

Illustrating The PSAR Process

The following example, along with all numerical values, is strictly notional. It is the Spring of 1998 and the NMD System Integrator (SI) is evaluating the performance and life cycle cost (LCC) estimates of its two GBI sub-contractors, Contractor X and Contractor Y. Each contractor is predicting a single shot kill probability (PKss)† of 0.8 against the threat of concern in the 2003 time frame. Each contractor has a different design for the booster and Exoatmospheric Kill Vehicle (EKV), however their 20 year LCC estimates are similar at approximately \$4B. The Systems Integrator is concerned because his own studies have shown that a higher value of PKss would be highly desirable in minimizing multiple shot (salvo) requirements against each of the incoming reentry vehicles (RVs). The system will have a specified number of interceptors to be deployed, so it is not possible to simply deploy more GBI to make up for shortfalls in individual interceptor performance.

The performance of the NMD system is defined in terms of the probability of negating all of the incoming RVs during an attack. We can assess the influence of PKss on performance and GBI launch requirements against a variety of threat scenarios using derived data as shown in Table 1. For example, if there is only one incoming RV, and two interceptors with PKss = 0.8 are salvoed, then the probability of successfully negating that RV is $1-(1-0.8)^2 = 0.96$. (This assumes that there is no shot-to-shot correlation. If the first shot misses, due to a bias in the system, then the second shot may miss on account of the same bias. In this case the resulting PK of the two shots could be less than 0.96.) If there are two incoming RVs and only one interceptor with PKss = 0.8 is fired against each RV, then the probability that both RVs will be negated is 0.8*0.8 = 0.64. Other combinations of incoming RVs and interceptors salvoed are shown in Table 1. Note that for four incoming RVs and a 0.8 value of PKss, three shots per RV (12 shots) are required to provide a probability greater than 0.96 that all RVs will be negated. If the value of PKss could somehow be improved to 0.9, only two shots per RV (8 shots) would be required for the same 0.96 probability of total negation. In the latter case 4 GBI are maintained in their silos for subsequent use.

No. Shots Salvoed Per RV	Number of INCOMING RVs 1	2	3	4	5
1	.800	.640	.512	.410	.328
2	.960	.922	.885	.849	.815
3	.992	.984	.976	.968	.961
4	.998	.995	.993	.992	.990

$P_{KSS} = 0.8$

No. Shots Salvoed Per RV	Number of INCOMING RVs 1	2	3	4	5
1	.900	.810	.729	.656	.590
2	.990	.980	.970	.961	.951
3	.999	.998	.997	.996	.995
4	.9999	.9998	.9997	.9996	.9995

$P_{KSS} = 0.9$

Table 1. Probability of Zero Leakers

The System Integrator directs the two contractors to estimate what design changes they would pursue to increase the PKss to 0.9 and to evaluate the influence of such changes on LCC. In order to provide each contractor with the broadest possible trade space, the SI does not specify reliability or availability as a separate requirement. A straw man block diagram shown in Figure 3 is provided to each contractor showing a hypothetical budget of probabilities that combine to provide the current estimate of PKss of 0.8. This straw man serves as a baseline from which

† This is the single shot kill probability given that the target cluster has been detected, tracked by GBR, and handed over to GBI. Normally these other probabilities are close to unity.

improvements may be measured. The contractors are given the freedom to explore any of the areas shown for performance improvement to reach the goal of PKss = 0.9.

Each contractor has a different approach to the problem. Contractor X believes that it would be very costly to achieve a reliability of greater than 0.96-0.97 in either the booster or the EKV. As a result, this contractor focuses on improving the probabilities of acquisition, target selection, intercept, and lethality. Contractor Y on the other hand believes that the biggest payoff is in increasing the reliability of both booster and EKV through the application of selected redundancy and use of very high reliability rated parts in certain areas. The following pages summarize the design solution of each of the two contractors.

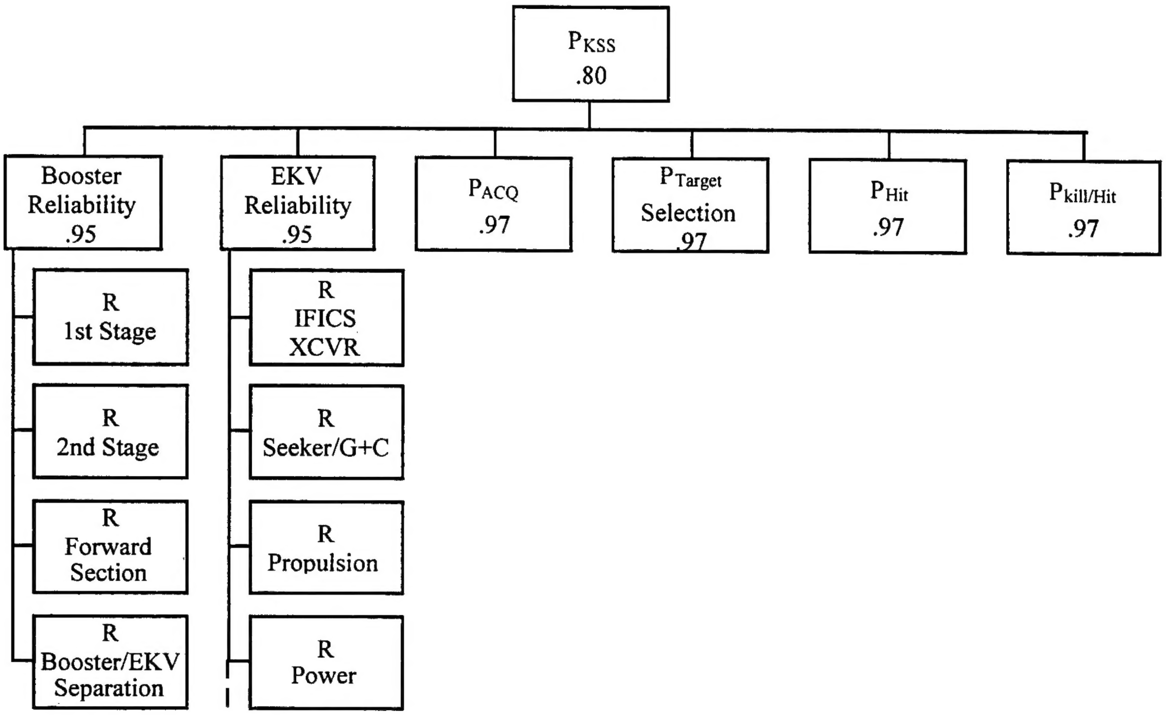

Figure 3. Hypothetical Probabilities Contributing to Single Shot Pk

Contractor X Design

Contractor X proposes a "wooden round" booster incorporating three stages which burn for a total of two and a half minutes. The booster is essentially dormant within its silo so there may be some small error in its inertial measurement unit (IMU) at launch. To compensate for this, Contractor X intends to maintain accurate position information of the booster during its flight in one of two ways. If the GBR turns out to be a phased array, the GBR would track the booster in addition to the target clusters. The large field of regard for the phased array design would permit GBR to track most of the booster fly-out in addition to the target clusters with minimal mechanical slewing. If the GBR turns out to be a needle beam dish radar, then a separate GPS receiver would be placed on the third stage to provide position data that cannot be obtained from the GPS receiver encapsulated within the shrouded EKV during the 2 and a half minutes of boost. Maintaining continuous knowledge of the booster in this way provides the earliest possible indication and warning that the booster may be off course due to a failure mode, so that an additional replacement booster can be launched. The booster's GPS receiver is also dormant within the silo, but it is "hot started" several seconds prior to liftoff by a ground based GPS receiver located at the missile field. The estimated reliability for this booster is .96. The cost of redesigning the booster is estimated to be $100 million.

Contractor X believes it can achieve 0.97 reliability for the EKV by adding two redundant nozzles in the divert thruster and changing the design of the EKV IFICS transceiver from a phased array to a higher gain body fixed dish design. The cost of this design

change including production is estimated to be $100 million. Their design allocates 30 percent of the PKss increase to reliability improvements (these alone would provide PKss=0.83), and the remaining 70 percent must be achieved through technical performance improvements. To increase the probability of the EKV acquiring the target cluster, they have redesigned the seeker to incorporate more sensitive optics (recently developed within their laboratories) which will acquire the target from farther away. This redesign in addition to the continuous booster tracking, will reduce the seeker error basket at EKV ignition permitting them to achieve an estimated value of 0.995 for target acquisition. The estimated cost of achieving this high probability is estimated to be $150 million. To increase the probability of selecting the RV within the cluster, they have introduced new discrimination algorithms which incorporate a Contractor X proprietary technique that can increase target selection probability to 0.99 at an estimated cost of $50 million. These high probability estimates raise the eyebrows of some government personnel reviewing the design.

Contractor X claims that they can increase the probability of hit from .97 to .99 by adding additional delta V for divert during the end game. The additional mass that would normally accompany this increase is offset by their proposal to use an ultra light weight alloy in designing the divert thrusters. The expected increase in LCC for these changes is $50 million. To increase the lethality, or probability of kill given a hit, they have selected an ultra dense alloy for the kill vehicle itself, and they intend to utilize target identity data to actually penetrate the RV at its most vulnerable point. Their propulsion system would preserve a small fraction of delta V to allow an optimal aspect angle at intercept. These design changes shift the lethality from .97 to .99 at an estimated cost of $50 million.

Table 2 summarizes Contractor X's estimated probabilities that contribute to achieving PKss=0.9 along with the estimated increase in LCC for each design change. The LCC numbers are based on a buy of 120 GBI since Contractor X estimates that 20 spares will be needed over the 20 year life cycle.

Probability Parameter	Baseline Value	Redesign Value	Cost of Redesign ($ in Millions)
R_{BOO}	.95	.96	100
R_{EKV}	.95	.97	100
P_{ACQ}	.97	.995	150
P_{TGTSEL}	.97	.99	50
P_{Hit}	.97	.99	50
$P_{Kill/Hit}$	.97	.899	50
Total	.799	.899	500

Table 2. Contractor X Redesign Summary

<u>Contractor Y Design</u>

From the beginning of the competition, Contractor Y has been skeptical of the wooden round concept, and now with the requirement of PKss=0.9 they are convinced that the booster must have some level of electrical power applied to it at all times. In this way their IMU accuracy can be better than Contractor X. They have heard through the grapevine of Contractor X's claims about target acquisition and discrimination, and consider these to be very high risk. In addition they don't believe that the exotic alloys that Contractor X intends to use are even producible. Their approach is to concentrate on reliability improvements to both the booster and EKV to achieve a reliability of 0.99 for each of these.

Contractor Y intends to use a three stage booster which burns for two minutes as opposed to two and one half minutes. They claim that because this booster permits a longer flight time for the EKV there is a greater probability that the EKV will receive one

or more in-flight target updates (IFTUs) and target object maps (TOMs). This translates into a greater probability of hit which is now estimated to be 0.98. In addition, for some scenarios, the longer flight time permits increased dwell time by onboard discrimination. They have also made improvements to their discrimination algorithms at a cost of $50 million, allowing them to revise their target selection probability upwards from .97 to .98.

Because the booster gyros are continuously operating within the silos, initial targeting errors are almost non-existent, and the booster can deliver the EKV very accurately to a point in space. In addition, power to the booster within the silo permits continuous monitoring of all critical subsystems through built in test. Subsystems which prove to be faulty may be changed out in most cases due to Contractor Y's modular design. Contractor Y had originally costed 20 spare GBI over the life cycle, but they have now revised that estimate down to 10 and intend to claim this as a savings in their new LCC estimate to the System Integrator.

The reliability block diagram for their new design is shown in Figure 4. Each stage of the booster is extremely reliable due to increased redundancy in the propulsion systems, and the use of gelled propellant in the third stage. The booster/EKV separation mechanism is now triple redundant with only a minor increase in cost. The EKV itself has some redesign with slightly more expensive subsystems to increase reliability. The IFICS transceiver shown is composed of all space rated parts and has proven to be extremely reliable based on prototypes demonstrated in the Brilliant Ears Program. Contractor Y is currently performing accelerated life testing on all critical components of both booster and EKV.

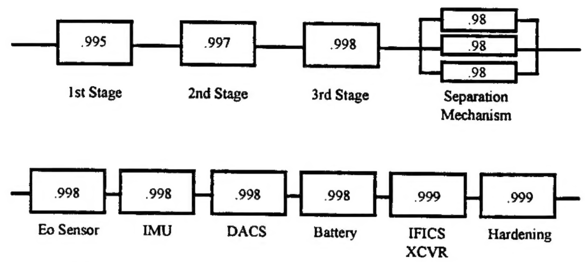

Figure 4. Contractor Y Reliability String

Table 3 summarizes Contractor Y's estimated probabilities that contribute to achieving PKss=0.9 along with the estimated increase in LCC for each design change. Note there is no cost associated with the increase in probability of hit since this is believed to be the natural result of the increased EKV fly-out time. A savings is claimed in LCC since the higher reliability will require fewer spares to be procured. As a result Contractor Y's revised LCC estimate is $4.25 as compared to $4.5B for Contractor X.

Parameter	Baseline Value	Redesign Value	Cost of Redesign ($ in Millions)
R_{BOO}	.95	.99	100
R_{EKV}	.95	.99	100
P_{ACQ}	.97	.98	50
P_{TGTSEL}	.97	.98	50
P_{Hit}	.97	.98	—
$P_{Kill/Hit}$	.97	.98	50
# of Spares	20	10	-100
Total	.799	.904	250

Table 3. Contractor Y Redesign Summary

The System Integrator and key government personnel review each design and weigh each for risk in performance, cost, and schedule. Contractor X argues (and the SI agrees) that to consider total impact on system LCC, it is necessary to look outside of the GBI element. One reason for this is that their

redesign of the IFICS transceiver to be a 4 inch dish reduces power requirements at the IFICS ground sites. They estimate that two IFICS sites could be eliminated at a savings of $300 million and therefore their design is actually less costly than Contractor Y's. Contractor Y counters by claiming that their redesign of on-board discrimination (which incurs $50 million to the GBI element) will relax certain requirements levied on the GBR designer thus reducing GBR LCC by $500 million.

After listening for two days to these arguments, the SI decides to initiate his own in house trades to look at PSAR requirements between the elements. The results of this study are due in the summer of 1998.

Impact on Acquisition Cost and NMD Supportability

Using PSAR requirements to open trade space to achieve the system performance, also allows flexibility in the remaining parameters of system acquisition, cost and schedule. The program manager is faced with balancing all three parameters to meet program goals and objectives. As discussed earlier, CAIV is required as a consideration in system acquisition to meet cost targets and control the cost of acquiring a system. Schedule is also important in that the program manager may be called upon to field the system within three years, once given a decision to deploy. As the trades are made by the elements over the PSAR requirements, the program manager must also assess the impact on meeting schedule requirements.

While innovative developments may improve PSAR requirements and lower LCC, these innovations can also carry schedule risks. If the technologies have never been tried and tested before, there can be risks in the integration that would have schedule impacts. The Program Office will select a Lead System Integrator (LSI) to design, develop, integrate, test and evaluate, produce, and, in concert with BMDO and the Services, plan the deployment, sustainment, and disposal of an NMD System. The LSI will work directly with the elements of the system to conduct and execute design trades that offer the greatest likelihood of achieving the NMD cost, schedule and performance goals. The LSI may have to maximize the use of commercial and non-developmental items to achieve schedule and affordability goals. This aspect leads to concerns and issue affecting the system supportability.

The PSAR approach was adopted for this program because the Government determined that specifying a system-level operational availability was essentially meaningless given a stringent system effectiveness requirement. This approach has two obvious considerations related to the supportability of the system, one potentially negative, and one positive. Commercial and non-developmental items are designed to a predetermined (at least from the perspective of the new use) maintenance concept. For many commercial off-the-shelf items, this usually involves a removal-replacement-disposal process. This may not be consistent with the overall concept for the system. Additionally, the system is dependent on industry to continue to supply the items or the acquisition program must purchase sufficient spares to span the anticipated system life. The positive, and we believe more significant, impact is when operational availability is not specified a priori, the PSAR trades between the system components will, by necessity, involve maintenance and supply alternatives.

Summary

This paper describes the method being used by Ballistic Missile Defense Organization's National Missile Defense Joint Program Office (JPO) to balance cost-performance trade-offs to meet both the User's requirement for Operational Effectiveness and the goals of DoD Acquisition Reform. The method replaces the requirement for a system level Operational Availability "design-to" requirement. In its place is a concept that balances Performance, Survivability, Operational Availability and Mission Reliability at the system level to meet the User's requirement for Operational Effectiveness. Operational availability remains a requirement at the subsystem level. This paper provides an illustration of the analytical method used to allocate and balance design parameters to meet Mission Effectiveness requirements. This method meets Acquisition Reform goals for cost-performance trades for large, complex "systems of systems."

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